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FINAL REPORT ON JPL CONTRACT 956108* FOR
"ANALYSIS OF JOVIAN LOW FREQUENCY RADIO EMISSIONS"

by

Donald A. Gurnett



I. Objectives of Contract

The objectives of this contract were to analyze the results of computer ray tracing of Jovian Low frequency radio emissions. Because the funds available for this study were quite limited, \$25K over approximately a three-year period, it was decided relatively early in the study to limit the study to one or two specific topic. The available funds were used to provide one-half time academic year support for two students, Mr. Robert Tokar and Ms. Joan Seery, plus a small amount of travel expense, computer charges, and publication fees. The topics selected for study were (1) the density of ions in the Io plasma torus and (2) the scattering of these ions by low frequency electromagnetic emissions detected by Voyager 1 in the Io plasma torus. These topics were considered to be important because the Jovian aurora is now believed to be caused by the pitch angle scattering and precipitation of ions into the atmosphere. The central question was whether the observed wave intensities were large enough to cause the necessary pitch angle scattering. Another important question was the mode of propagation of the waves, which could be either right-hand polarized whistler-mode waves, or left-hand polarized ion cyclotron waves.

* This work was prepared for the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

II. Results

The first phase of the study was an investigation of the ion density profile using whistler dispersion measurements obtained from Voyager 1. The Voyager plasma instrument provided measurements of all ion species except H⁺. By combining the measured plasma densities with the whistler dispersion measurements it was possible to determine the scale height and absolute density of H⁺ ions in the vicinity of the plasma torus. This study was conducted by Mr. Robert Tokar and was published in the Journal of Geophysical Research (see the list of abstracts in Section III).

The second phase of the study was a theoretical analysis of the modes of propagation of low frequency electromagnetic emissions in the torus. The propagation of low frequency electromagnetic emissions in the Io torus is complicated by the numerous ion species in the torus. Each ion species has a different cyclotron frequency and interacts with the wave spectrum in a different way. These interactions are further complicated by polarization reversal effects. At a frequency called the crossover frequency, one of which occurs between each adjacent pair of ion cyclotron frequencies, the polarization is reversed. This means that whistler-mode waves (right-hand polarized) generated by electrons in the torus can be converted to ion cyclotron waves (left-hand polarized) and vice versa. Since Voyager 1 observed what is widely interpreted as whistler-mode radiation in the torus, this polarization reversal mechanism provides a way of producing ion cyclotron waves. Left-hand polarized ion cyclotron waves are usually regarded as more

effective in scattering ions because the waves and particles rotate in the same sense with respect to the magnetic field. These polarization reversal effects and rough estimates of the ion diffusion coefficient were published by Gurnett and Goertz [1983].

Because it was very difficult to make accurate analytical estimates of the ion scattering by waves in the torus, a project was undertaken to numerically evaluate the ion diffusion coefficients in the torus using the observed Voyager 1 wave intensities. This project was assigned to Ms. Joan Seery as her M.S. thesis project. The numerical evaluation of the diffusion coefficients was an involved effort because it first required the tracing of a wave trajectory along the magnetic field line, and at the same time keeping track of the wave intensity and polarization. Meanwhile to determine the diffusion coefficient an ion trajectory must be computed along the magnetic field line and the contribution to the ion diffusion must be computed at each point, considering all waves that reach that point. The physically relevant quantity is the bounced-average diffusion coefficient.

The numerical procedure to carry out this evaluation has now been completed and is described in Ms. Seery's M.S. thesis. The results show that the observed wave intensities produce significant ion diffusion effects in the ion torus. It is not, however, certain that the diffusion coefficients are sufficiently large to account for the Jovian aurora. The main uncertainty has to do with the wave intensities below 10 Hz, and in the region outside of the torus, neither of which were measured by Voyager. The results of Ms. Seery's thesis are now being prepared for publication.

III. Abstracts of Publications and Reports

1. Tokar, R. L., D. A. Gurnett, and F. Bagenal, "The proton concentration in the Vicinity of the Io Plasma Torus," J. Geophys. Res., 87, 10,395, 1982.

This paper uses an improved model for the plasma distribution in Jupiter's magnetosphere to determine the light ion concentration in the vicinity of the Io plasma torus from whistler dispersion measurements. The model used assumes that the plasma is in diffusive equilibrium under the action of centrifugal, gravitational, and ambipolar electric field forces. The study provides an estimate of the plasma concentration at intermediate and high latitudes along field lines through the Io plasma torus. The method employed is to combine the Voyager 1 plasma wave instrument whistler observations with the Voyager 1 plasma instrument heavy ion charge concentrations throughout the Io torus to determine the light ion charge concentration along the whistler propagation paths. Because the light ion source is probably Jupiter's ionosphere and because Jupiter's atmosphere is primarily hydrogen, the light ions are taken to be protons. Whistlers at 13 L values between $L = 5.25$ and $L = 5.85$ are analyzed. Values of NL^2 , the total number of ions per unit L multiplied by L^2 , are calculated and the ratio $NL^2(\text{protons})/NL^2(\text{electrons})$ is found to have an average value of 0.2. This ratio is used to give a rough estimate for the ionospheric source strength.

2. Gurnett, D. A., and C. K. Goertz, "Ion cyclotron waves in the Io plasma torus: Polarization reversal of whistler mode noise," Geophys. Res. Lett., 10, 587, 1983.

Because of the presence of multiple ion species in the Io plasma torus whistler mode noise can be converted to ion cyclotron waves via a polarization reversal process at the local crossover frequency. Using whistler mode intensity measurements in the Jovian magnetosphere from Voyager 1 we estimate the pitch-angle diffusion rates that would occur if the noise is converted to ion cyclotron waves. Typical pitch-angle diffusion coefficients range from $D_{\alpha\alpha} \approx 10^{-6} \text{ sec}^{-1}$ for protons resonating near the equator to $D_{\alpha\alpha} \approx 10^{-4} \text{ sec}^{-1}$ for 10 keV O^+ ions resonating at high latitudes. Although complete bounce averaged diffusion coefficients have not yet been computed, preliminary estimates indicate that the energetic ion precipitation caused by these waves may be able to account for the EUV auroral emissions at the foot of the torus field lines.

3. Seery, J. R., "Ion diffusion in the Io plasma torus," M.S. Thesis, Dept. of Physics and Astronomy, University of Iowa, Iowa City, Iowa, May 1984.

Pitch-angle scattering of protons in resonance with left-hand polarized ion cyclotron waves and right-hand polarized whistler mode waves was studied as a means for producing the EUV auroral emissions at the foot of the Io torus field lines. A polarization reversal process can convert whistler mode noise to ion cyclotron waves at the local crossover frequency due to the presence of multiple ion species in the Io plasma torus. Local crossover frequencies were computed along a dipole field line at $L = 5.85$ to determine the latitudes at which the polarization reversal occurs. Resonance frequencies for right-hand and left-hand polarized waves were then calculated along the field line using computed values of resonance energies for parallel propagation. Using electric field measurements of noise detected by Voyager 1, believed to be due to whistler mode waves, bounce averaged diffusion coefficients were computed for protons ranging in energy from 10 keV to 3 MeV with equatorial pitch angles ranging from 5° to 85° . For a given energy, the diffusion coefficient increased with pitch angle for small pitch angles, peaked, and decreased to zero at a cutoff pitch angle. At low energy (10 keV) only the cyclotron resonance contributed to the diffusion coefficient, but the contribution from anomalous resonance increased as the energy increased. The magnitudes of the coefficients indicate that the diffusion is intermediate between strong and weak. While pitch-angle scattering of protons contributes to charged particle precipitation into the atmosphere, another factor is primarily responsible for the aurora.